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BEHAVIOR OF ORIENTED CONCRETE CORBELS BASED ON REINFORCED STRUT AND TIE

A Thesis Submitted to Council of College of Engineering,
University of Diyala in Partial Fulfillment of the
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Engineering

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CHAPTER ONE

INTRODUCTION

1.1 General

Corbels, or brackets, are very important structural members for supporting precast beams, gantry girders and bridges. They are usually built monolithically with columns or walls to support heavy concentrated loads as shown in Figure (1-1). Reinforced concrete corbels have become a common feature in building construction with the increased use of precast reinforced concrete elements for the construction of buildings and bridges.

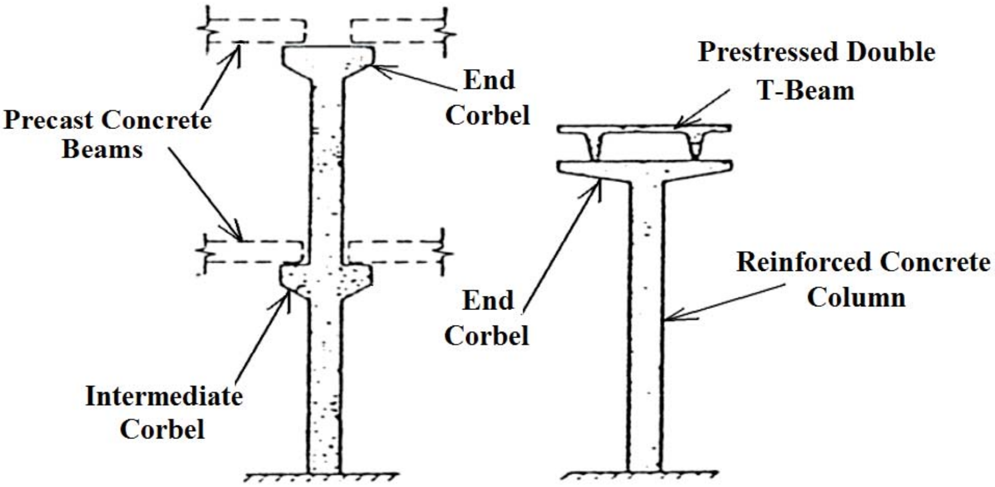


Figure (1-1): Precast concrete column and corbels, (Salman, et al., 2014)

The American Concrete Institute Code (ACI 318-14) describes corbels as short cantilevers that tend to act as simple trusses or deep beams, rather than shallow beams, which are designed according to shear friction theory (SF) or using strut and tie modeling (STM).

Corbels are primarily designed to resist vertical loads and horizontal actions. Shrinkage, thermal deformation and creep of the beam and/or breaking of a bridge crane that are supported cause these horizontal actions. More specifically, they cause direct tension in corbel main or tie reinforcement.

1.2 Reinforced Concrete Corbels Failure Modes

There are six failure modes of reinforced concrete corbels, Elzanaty summarized these as below (Elzanaty et al., 1986):

1.2.1 Diagonal Splitting Failure

It develops along the diagonal compression strut which propagates from the applied load point toward the bottom corbel column connection as shown in Figure (1-2).

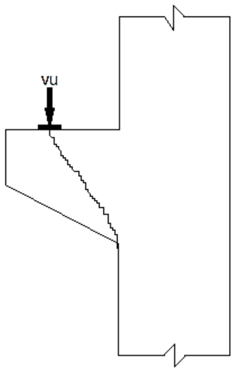


Figure (1-2): Diagonal splitting failure of corbel

1.2.2 Shear Friction Failure

It begins from the corbel upper corner, then propagates vertically to the lower fiber, and causes separation of the corbel from the column face as shown in Figure (1-3).

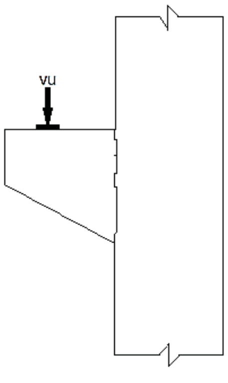


Figure (1-3): Shear friction failure of corbel

1.2.3 Anchoring Splitting Failure

It happens by rotating end of corbel when the applied load is so close to the free end or when high flexural bond stresses can combine with high local bond stresses as shown in Figure (1-4).

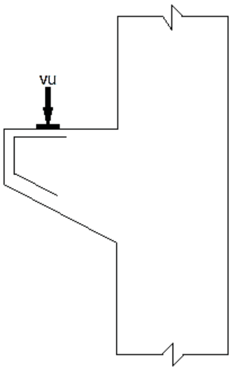


Figure (1-4): Anchoring splitting failure of corbel

1.2.4 Vertical Splitting Failure

It occurs usually due to the direct tension effect of the horizontal load as shown in Figure (1-5).

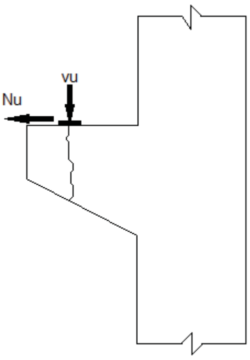


Figure (1-5): Vertical splitting failure of corbel

1.2.5 Bearing Failure

The concrete may crush underneath the applied load area when too small or very flexible bearing plates, or the corbel is too narrow as shown in Figure (1-6).

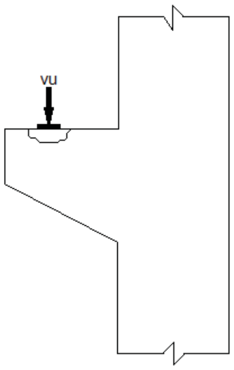


Figure (1-6): Bearing failure in corbel

1.2.6 Flexural Failure

Due to excessive yielding of the main reinforcement, the flexural cracks become extremely wide as shown in Figure (1-7).

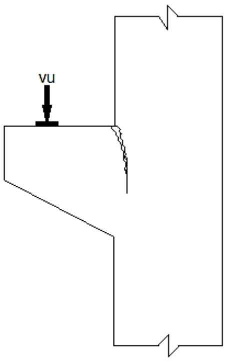


Figure (1-7): Flexure failure of corbel

1.3 Provisions of Corbels

The detailing of the corbel reinforcement has a major importance. Failure of the member can be attributed in many cases to incorrect detailing that does not realize full anchorage development of reinforcing bars, (ACI 318M, 2014).

1.3.1 Dimensional Limits

- Effective depth (d) for a corbel is usually calculated at the column face, Figure (1-8a), (ACI 318-14).
- Overall depth of corbel at the free face near the bearing area should be at least *0.5d*.

- The bearing area from the face of support shall not exceed:

a) End of the straight portion of the main reinforcement.

b) Interior face of the transverse anchor bar.

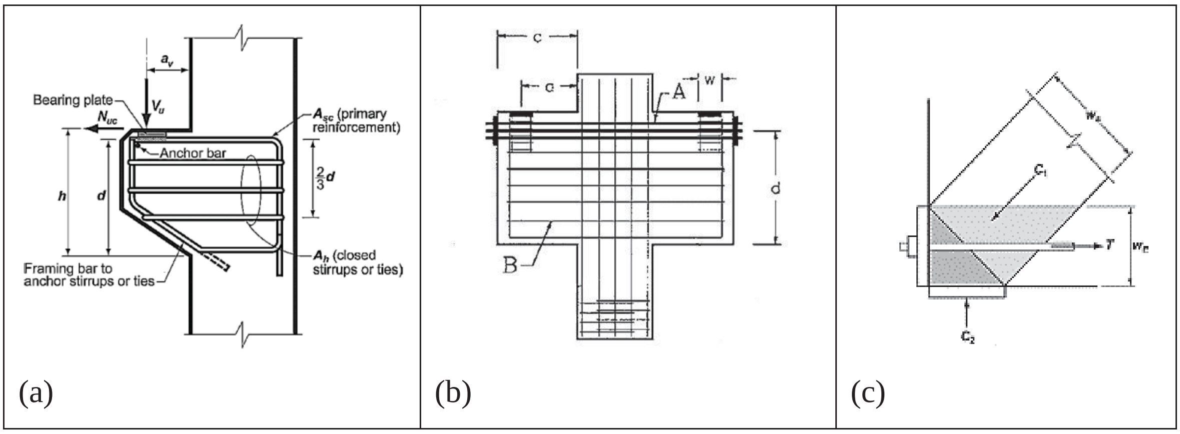
1.3.2 Reinforcement Detailing Limits

- Area of main reinforcement (A_s), should be at least the greatest of (a) through (c):
  - *a)* $A_f + A_n$
  - *b)* $(2/3)A_{vf} + A_n$
  - c) $0.04(f'c/fy)(b\,d)$

  Where A_f is the area of reinforcement that resists design moment, A_n is the area of reinforcement that resists tensile force from horizontal load N_u, and A_{vf} is the area of shear-friction reinforcement.

- Total area of horizontal secondary reinforcement parallel to main reinforcement A_h, should be at least $A_h = 0.5(A_s - A_n)$.
- For a corbel with a/d less than 1.0, horizontal secondary reinforcement is usually provided, while horizontal and vertical secondary reinforcement are used for corbel with a/d greater or equal to 1.
- The main reinforcement should be anchored at the front face of the corbel by either (a), (b), or (c):
  - a) A weld to a transverse bar, i.e. anchor bar, of at least equals to size that is designed to develop *fy* of main reinforcement as shown in Figure (1-8a).
  - b) Bending the main reinforcement back to form a horizontal loop.
  - c) Other means of anchorage that develops *fy* such as thread and mechanical anchors, i.e. steel plate, of the main longitudinal bars to avoid any possibility of anchorage failure as shown in Figure (1-8b), (Stephen et al., 1996) and Figure (1-8c), (ACI 318-14).

- Secondary horizontal reinforcement shall be uniformly distributed within (2/3)d measured from the main reinforcement.



(a) (b) (c)

Figure (1-8): Anchorage of main reinforcement; (a) Anchor bar, (ACI 318M, 2014), (b) Mechanical anchoring steel plate, (Stephen, et al., 1996), (c) Tensile force anchored by a plate, (ACI 318M-14, R23.2.6).

1.4 Analysis and Design Methods of Corbel

According to ACI 318-14 provisions, there are two different methods to analyze and design RC corbels; SF and STM. SF can be used when the a/d is less than or equal 1, section 16.2 (Brackets and Corbels) of ACI 318-14 and section 22.9. On the other hand, Chapter 23, ACI 318-14, (Strut-and-Tie Models) can be used for the analysis and design of corbels when a/d is less than 2.

1.4.1 Shear Friction Approach

The shear friction analogy is familiar to most engineers in practice and to most researchers in investigations. It is a valuable and simple tool which can be used to estimate the maximum shear force transmitted across a cracked plane, where one face of crack slides relatively to the other. The applied shear is held by friction between the crack faces and by dowel action of the reinforcement crossing the crack as shown in Figure (1-9). It is used for the design of short corbels with $a/d \leq 1.0$ only wherein a control of the interface stresses is necessary to prevent a possible shear failure (ACI 318-14). More specifically, it is used with precast concrete structural connections for estimating the load capacity of interfaces between precast members and cast-in-place concrete. In addition, it is used for calculating the residual shear capacity of cross sections which are weakened by cracking (Mattock, et al., 1976).

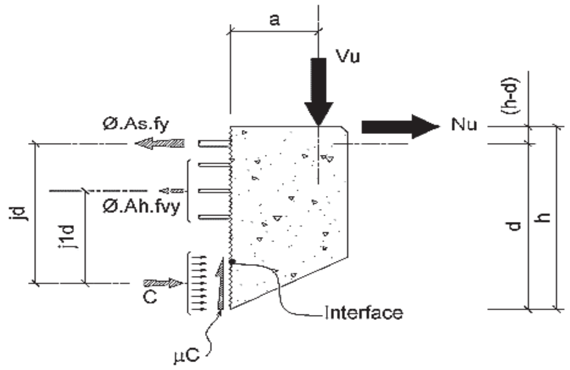


Figure (1-9): Corbel free-body diagram, (Mattock, et al., 1976)

1.4.2 Strut and Tie Modeling

The Strut-and-tie modelling is a generalization of the truss analogy in which a structural continuum is transformed into a discrete truss with compressive forces being resisted by concrete and tensile forces by reinforcement and connected by nodes, Figure (1-10). This method is based on the lower bound theorem of plasticity (Kassem, 2015).

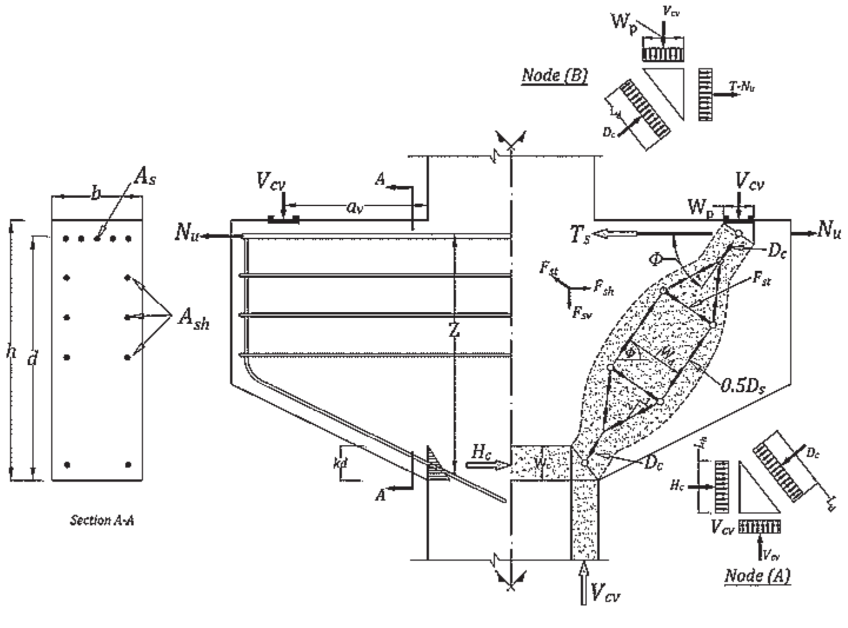


Figure (1-10): Geometry and STM with forces acting on corbel, (Kassem, 2015).

In STM, the failures are basically introduced either by the steel yield reaching or the concrete compressive strength reaching. This implies that the concept of shear failure as a particular failure criterion is excluded. In addition, failures caused by insufficient anchorage of the reinforcement are possible. Such failures should be avoided by proper detailing and the maximum value is related to the compression failure criterion. The geometric limitations are shown in Figure (1-11); yielding the following equations (1-1) and (1-2), (Hagberg, 1983):

$\tan(\beta_{max}) = (a + w/2)/d$ ....(1-1)

and

$\max x = w \cdot \cos(\beta_{max})$ ....(1-2)

Where

β_{max} = maximum inclination of compression member

w = width of bearing plate

x = width of strut

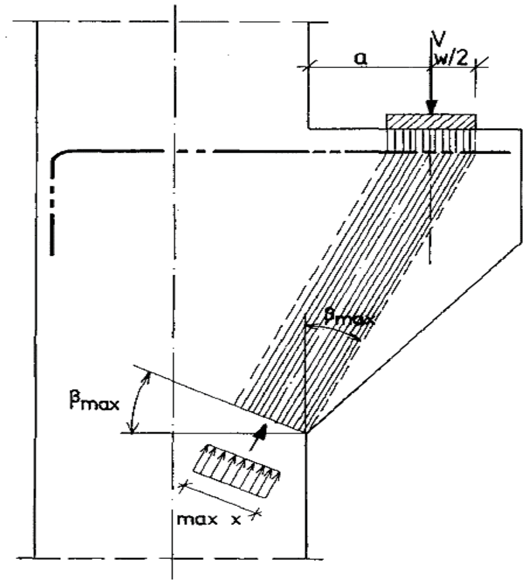


Figure (1-11): Relation between geometry and maximum capacity, (Hagberg, 1983)

1.5 Objectives of the Present Work

The main objective of the present work is to investigate the performance of STM when reinforcing the compressive struts by steel bars. This could help to remove the zones that STM does not care about (the zones where the struts and ties do not pass through) to reduce weight of specimen and to provide openings for essential services. In other words, the current work takes into consideration the paths of struts and reinforcing them according to ACI 318M-14 with different a/d values.

1.6 Thesis Layout

The present thesis is offered in five chapters:

- **Chapter One** presents a general introduction about RC corbels, SF, STM, in addition to the objectives of the study.
- **Chapter Two** presents a review of some previous research works with experimental studies that carried out on corbels, STM and SF.
- **Chapter Three** deals with the used construction materials in addition to the experimental work details.
- **Chapter Four** deals with presenting test results of the laboratory specimens, discussing and evaluating the experimental results of the present work.
- **Chapter Five** provides the conclusions drawn from this study, recommendations and suggestions for further work.

Behavior of Oriented Concrete Corbels based on Reinforced Strut and Tie

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ABSTRACT

The main objective of the current study is to investigate the behavior of reinforced concrete corbels when reinforcing their struts and ties as compressive and tensile members, respectively according to ACI 318M-14. Fifteen reinforced concrete corbel specimens were carried out experimentally with different shear span to effective depth ratios (a/d). The experimental program consisted of casting and testing six groups of corbel specimens with constant dimensions of 120 mm width, 400 mm height and 360 mm effective depth. The first three groups contained intermediate corbel specimens, while the other three ones contained end corbel specimens. The a/d value was 0.5 for the first and fourth groups, 1 for the second and fifth groups, while it was 1.5 for the third and sixth groups.

Each group of the intermediate corbel consisted of two specimens; conventionally reinforced reference corbel and proposed frame that took its geometry from the Strut and Tie Model (STM) stress paths, ACI 318-14. On the other hand, every end corbel group contained three specimens; the conventionally reinforced reference in addition to two proposed frames that one of them had covered tie and the second one had uncovered tie.

The experimental ultimate capacity, load-deflection response, first crack load, deflection at first crack, cracks characteristics such as type, width and propagation, strain values in steel bars and in concrete surface, the contribution of reinforcement to the strengths of struts and ties in addition to failure modes are also investigated.

The experimental results show that the load-deflection curves in proposed specimens exhibited more linearity than that of the reference specimens except near the failure load due to the fact that the applied load transferred more directly into the independent prismatic reinforced struts of the proposed specimens.

The proposed specimens did not exceed the conventional specimens in terms of experimental ultimate capacity, but in all cases, they exceeded the theoretical STM design load. More specifically, the specimens with a/d = 0.5, 1 and 1.5 show a decline in the experimental ultimate capacity compared with their reference specimens by about 2-16%, 0-18% and 23-30%, respectively, but in all cases, their theoretical design loads of STM, ACI 318-14 remained less than the experimental ultimate capacity by about 11-25%, 18-33% and 12-42%, respectively. Accordingly, it could be said that the proposed specimens are good alternatives for the reference corbels because of cost saving, weight reducing and providing a front side area for services which amounted to 13-52%, 1.7-15% and 14-52%, respectively in comparison with the reference specimens. That can be attributed to the fact that the stresses are actually transferred according to stress paths of STM, ACI 318-14.

The test results also indicated that when a/d increased by about 50-200%, the load capacity of the reference specimens decreased by about 17-36%, while the deflection, crack number and crack width increased by about 10-35%, 19-217% and 7-140%, respectively. In related context, the load capacity of the proposed specimens decreased by about 15-55%, when a/d increased by about 50-200%, while the deflection, crack number and crack width increased by about 13-49%, 0-122% and 10-420%, respectively. It is worth to mention that in some proposed specimens, due to different failure modes, crack width values decreased by about 7-29% when a/d increased by about 50-200%.

Measuring strain values experimentally enabled in estimating the reinforcement contribution to the concrete strength of the struts, 22%, 17%, and 26% when a/d was 0.5, 1 and 1.5, respectively. They were less than that estimated via ACI 318M-14 equations by about 8%, 32% when a/d was 0.5 and 1, while in case of a/d was 1.5, the contribution exceed ACI 318M-14 equations by about 4%.